Simulations of magnetic fields in filaments

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ABSTRACT

The intergalactic magnetic field within filaments should be less polluted by magnetised outflows from active galaxies than magnetic fields in clusters. Therefore, filaments may be a better laboratory to study magnetic field amplification by structure formation than galaxy clusters which typically host many more active galaxies. We present highly resolved cosmological AMR simulations of magnetic fields in the cosmos and make predictions about the evolution and structure of magnetic fields in filaments. Comparing our results to observational evidence for magnetic fields in filaments suggests that amplification of seed fields by gravitational collapse is not sufficient to produce IGM fields. Finally, implications for cosmic ray transport are discussed.

Subject headings: galaxies: active - galaxies: clusters: cooling flows - X-rays: galaxies

1. Introduction

Clusters of galaxies are known to host magnetic fields with strengths that are of the order of μG and coherence scales that are of the order of 10 kpc (Carilli & Taylor 2002; Govoni et al. 2004). In cool cores of clusters remarkably high fields have been found: E.g. Blanton et al. (2003) have found magnetic fields as high as 11 μG in the cool core of A2052. Knowledge about cluster magnetic fields comes from synchrotron and inverse Compton radiation as well as Faraday rotation measurements. Based on analyses of rotation measure maps in three cluster, Vogt & Enßlin (2003) have derived spectral indices of 1.6 to 2.0 (Vogt & Enßlin 2005;

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Enßlin & Vogt 2003). However, they probe mostly smaller scales than those considered here and, to our knowledge, there are no reliable observations on larger scales.

Meanwhile, the origin of cluster magnetic fields in the IGM remains unclear. It has been suggested that they are primordial (Murgia et al. 2004; Banerjee & Jedamzik 2003; Dolag et al. 2002; Gnedin et al. 2000), i.e. that a seed field that has formed prior to recombination is subsequently amplified by compression and turbulence. In Dolag et al. (2002), the average fields in the core of clusters at redshift 0 were found to range between 0.4-2.5 μG if the initial seed fields at redshift 15 were of the order of a nanogauss. Alternatively, it has been proposed that the magnetic field was of protogalactic origin (Kulsrud et al. 1997) or that it had been produced by a cluster dynamo (Ruzmaikin et al. 1989; Roettiger et al. 1999). Others conclude that magnetic fields can be produced efficiently in shocks by the Weibel instability (Medvedev et al. 2004) or by small-scale plasma instabilities (Schekochihin et al. (2005)). Finally, it has been suggested that the IGM has been magnetised by bubbles of radio plasma that are ejected by AGN (Furlanetto & Loeb 2001). A growing number of large, magnetised bubbles is being discovered in clusters of galaxies (Bîrzan et al. 2004) and simulations show that they may not be very long-lived (Brüggen et al. 2005). Presumably, the magnetised bubble plasma gets mixed with the IGM and is thus likely to contribute to present cluster fields. However, this form of AGN activity has only been discovered in the center of massive clusters, so that the IGM in filaments ought to be much less affected by magnetised plasma ejected from AGN.

Bagchi et al. (2002) have discovered diffuse radio emission from a large network of filaments of galaxies that span several Mpc. Assuming that this emission is synchrotron emission the minimum-energy argument yields a minimum field strength of $B \sim 0.3\,\mu$G.

The purpose of this paper is to simulate the magnetic field in filaments with sufficient resolution in order to make predictions about their magnitude and structure. There have been few cosmological simulations that include magnetic fields, and most of them focus solely on galaxy clusters. So far there are no computations that can make reliable predictions on field amplifications in filaments.

Obviously, this project poses significant computational challenges as we have to cover a wide range of scales. In order to simulate structure formation on a cosmologically relevant scale, the box has to be many Mpc across. At the same time we wish to resolve the thin filaments well enough to make statements about the magnetic field evolution within them. In an attempt to bridge this large range of scales we used the adaptive-mesh PPM code FLASH that provides full support for particles and cosmology.

2. Simulation

The initial conditions for our simulations are the publicly available conditions of the Santa Barbara cluster (Frenk et al. 1999) at redshift $z = 50$. Consequently, our cosmological parameters are those of the Santa Barbara cluster, i.e. $H_0 = 50$ km s^{-1}Mpc^{-1}, $\Omega_m = 1$, $\Omega_\Lambda = 0$. The cluster perturbation corresponds to a 3σ peak in density smoothed over 10 Mpc. We assumed standard cosmic composition, i.e. the Hydrogen and Helium fractions were 0.7589 and 0.2360, respectively. Star formation has been neglected.

Our computational domain was a cubic box of side $L = 64h^{-1}$ Mpc. FLASH is a modular block-structured AMR code, parallelised using the Message Passing Interface (MPI) library. FLASH solves the Riemann problem on a Cartesian grid using the Piecewise-Parabolic Method (PPM) and, in addition, includes particles that represent the dark matter. Our simulation included 2097152 dark matter particles with a mass of $7.8 \cdot 10^9 M_\odot$ each. We chose a block size of 16^3 zones and used periodic boundary conditions. The minimal level of refinement was set to 4 which means that the minimal grid contains $16 \cdot 2^{(4-1)} = 128$ zones in each direction. The maximum level of refinement was 10, which corresponds to an effective grid size of $16 \cdot 2^{(10-1)} = 8192$ zones or an effective resolution of $7.8h^{-1}$ kpc. This was the maximum that we could afford computationally.

The mesh is refined and derefined automatically depending on the dark matter density. It was set up such that no more than 8 dark matter particles occupied one computational cell. We first ran a simulation with only 8 levels of refinement, then identified three regions that contained filaments, and reran the simulation with 10 levels of refinement. In addition to refining on the dark matter we enforced full refinements in the regions that contain the filaments. However, the dark matter distribution, represented by the particles, is not refined.

In order to achieve satisfactory accuracy even on small scales we decided to implement a passive magnetic field solver in FLASH that keeps the divergence of the magnetic field very small. The price for this is that, currently, we are unable to compute the full MHD equations. However, we find that the magnetic fields in the ICM will rarely be dynamically important and, at this level, they are described with sufficient accuracy by a passive field solver.

We chose to implement the passive field solver described by Pen et al. (2003), which solves the magnetic field on a staggered mesh. It is straightforward to show that if the magnetic field is evolved on a staggered instead of a centred grid, the magnetic field will

remain divergence-free provided that it was divergence-free to start with (Evans & Hawley 1988). Every time step the magnetic field is evolved using a total-variation diminishing (TVD) scheme that solves

$$\partial\mathbf{B} = \nabla \times (\mathbf{v} \times B) - \frac{3}{2}\frac{\dot{a}}{a}\mathbf{B} \ , \tag{1}$$

where $\mathbf{B} = \mathbf{B}_{\rm physical}/a$ and a is the scale-factor. The thus evolved field is then interpolated with a third-order scheme to the cell centres.

Initially we set up a divergence-free field using the vector potential. The magnetic vector potential $\tilde{\mathbf{A}}(k)$ was composed of 512 Fourier modes with random phases and amplitudes that were drawn from a Gaussian distribution. $\tilde{\mathbf{A}}$ was then scaled as $k^{-\alpha}$, where k is the wavenumber of the mode. This leads to a magnetic power spectrum of $P_B(k)\,dk \sim k^{2(2-\alpha)}\,dk$. Here, α was chosen to be 2. The vector potential was then Fourier-transformed into physical space with a Fast Fourier Transform. The field was normalised such that the physical mean field at redshift 50 was $3 \cdot 10^{-11}$ G.

In agreement with what Dolag et al. (2002) have found using SPH simulations, we verified that the resulting magnetic fields are very insensitive to the topology of the initial field at $z = 50$. Even if one starts with an initially uniform magnetic field, the results are not significantly different. The field at any time obviously depends on the strength of the initial field, but since the field is only evolved passively, the normalisation is arbitrary.

3. Results and Discussion

In Fig. 1 we show the density distribution in a slice through the center of the computational box where a massive cluster has formed. ($r_{200} = 2.6$ Mpc, total mass $\sim 1.1 \cdot 10^{15} M_\odot$) The cosmic web with its filaments is clearly visible. Fig. 2 displays the magnitude of the magnetic field in the same same slice as in Fig. 1. Evidently the magnetic field correlates with density as one would expect from the conservation of magnetic flux which implies $B \propto \rho^{2/3}$. However, we find that in some regions the magnetic field is amplified significantly beyond $B \propto \rho^{2/3}$ which is what one would expect from compression alone. This is caused by shear flows and occurs mainly in the outskirts of the cluster and near accretion shocks.

The mass-averaged field in the center (within $0.1\, r_{\rm vir}$) of the cluster increases by a factor of ~ 7000. The correlation length is of the order of 30 kpc and the modulus of the rotation measure goes up to 1000 rad m^{-2}. This agrees with findings by Dolag et al. (2002) who

use SPH simulations of clusters, which is a fundamentally different computational technique from the one used here.

In Fig. 3 we show the three-dimensional power spectrum of the magnetic field energy $\epsilon \sim B^2$ for various box sizes centred on the cluster. Until numerical effects near the resolution limit set in, the power spectrum is well described by a power-law with an index of $\sim 5/3$. Thus, the mere amplification of seed fields by gravitational collapse and shearing motions reproduces cluster fields with a power spectrum that is in very good agreement with observations (Vogt & Enßlin 2005). Similar slopes were found in Rordorf et al. (2004).

In the filaments the magnetic field increases by a factor of $\sim 10-300$ between a redshift of 50 and 0.5. In Fig. 4 we zoom into a region that contains two typical filaments. The mass-averaged temperature in the filaments is $\sim 10^6$ K. Shown are the magnitude and orientation of the magnetic field. In the filaments the magnetic field goes up to ~ 3 nG which corresponds to an amplification by a factor of 100. One should note that our grid simulations are maximally refined in the filaments and are thus expected to yield more reliable results than SPH simulations.

If indeed filaments host magnetic fields of the order of $B \geq 0.3\,\mu$G, as suggested by Bagchi et al. (2002), this would require seed fields of the order of 10^{-9} G at $z \sim 50$. Seed fields of this order of magnitude may be hard to produce (see also Dolag et al. (2005)). Consequently, this would call for alternative origins for IGM magnetic fields (Kronberg 2004). Future observing campaigns with instruments such as LOFAR and the SKA are expected to shed some light on magnetic fields in the early universe.

As is evident from Fig. 4, we find that magnetic fields are predominantly oriented in a direction parallel to the filaments. This is true for all filaments in our simulation volume. As material accretes onto the filaments, the magnetic fields are compressed parallel to the filaments and, as clusters and groups form, the filaments are stretched. This field topology could have several interesting implications: For one, the diffusion length of cosmic rays along filaments may be much greater than out of the filaments. This makes filaments efficient traps for cosmic rays and could help to explain the diffuse radio emission seen along the entire length of the filament in Bagchi et al. (2002). Secondly, heat conduction is likely to be more efficient along filaments than elsewhere. This could lead to heat being conducted from the outskirts of the clusters into the filaments.

Moreover, we have calculated the cumulative volume filling fraction of the magnetic field. It shows that only 1% of the volume is filled with magnetic fields above 1 nG. Our filling curve is close to the results of Dolag et al. (2005). As a consequence UHECR deflection of more than 1° can only happen if a cosmic ray passes a cluster region. We found that for 99% of trajectories chosen randomly through our box protons with $E \geq 10^{20}$ eV would be deflected by less than 0.2°. These results are well consistent with first positive indications of UHECR clustering (Farrar 2005). Upcoming UHECR detectors as the Pierre Auger experiment may probe the large-scale magnetic fields directly.

Finally, in Fig. 5 we plot the magnetic field strength along a line that goes through the center of the cluster and on a line that cuts through the most massive filament in our computational box. The relative strengths of the fields in clusters and filaments are evident.

Obviously, in these kinds of simulations the question of grid convergence arises. We have run our simulation at three different levels of refinement and compared the results. While the field amplification typically increases with the resolution, we found only a very small difference between runs with 9 and 10 levels. However, one should note that the resolution of the underlying dark matter density and velocity field is restricted by the dark matter particle mass, which is not refined.

Summary: We have produced a cosmological AMR simulation with a passive magnetic field solver on the basis of the FLASH code. In agreement with work by others, we find that within the cluster seed fields are amplified by a factor of ~ 7000 between $z = 50$ and today. We find that cluster magnetic fields follow a power spectrum with index 5/3. Within filaments the amplification is typically $10 - 300$ and the fields are aligned with the filament. The magnetic field of the IGM correlates roughly linearly with temperature.

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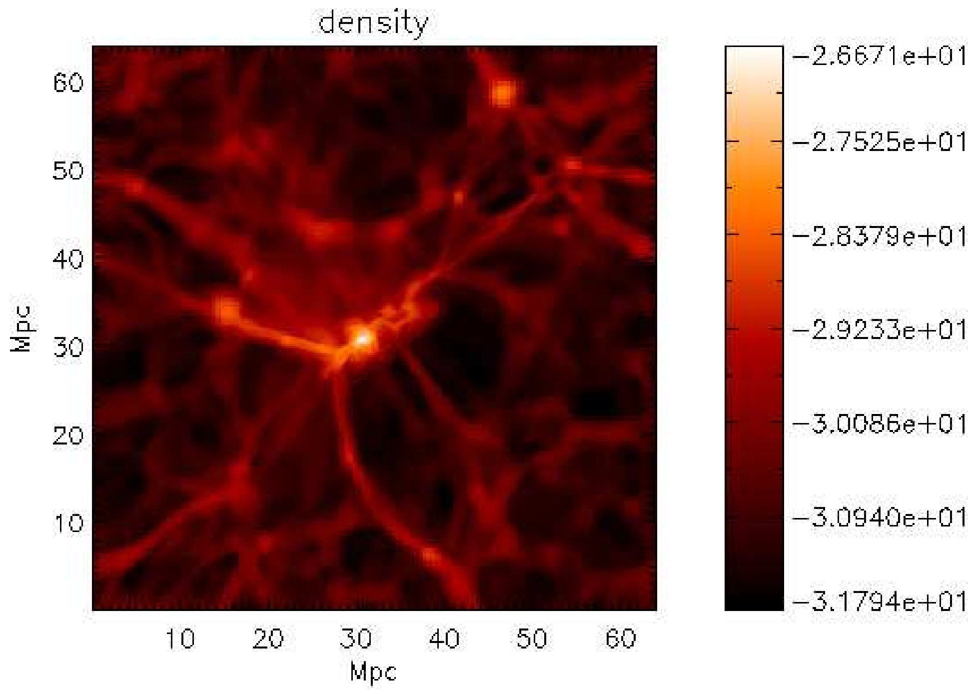

Fig. 1.— Logarithmic density plots in slices through the center of the computational box at $z = 0.5$. Density units are cgs.

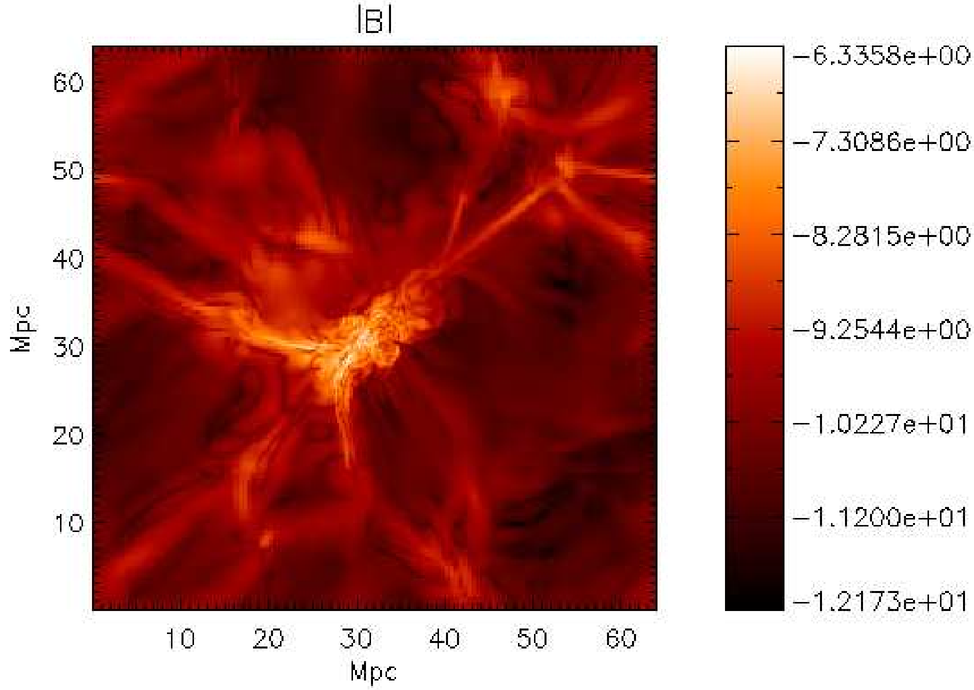

Fig. 2.— Logarithmic plots of the magnitude of the magnetic field in slices through the center of the computational box at $z = 0.5$.

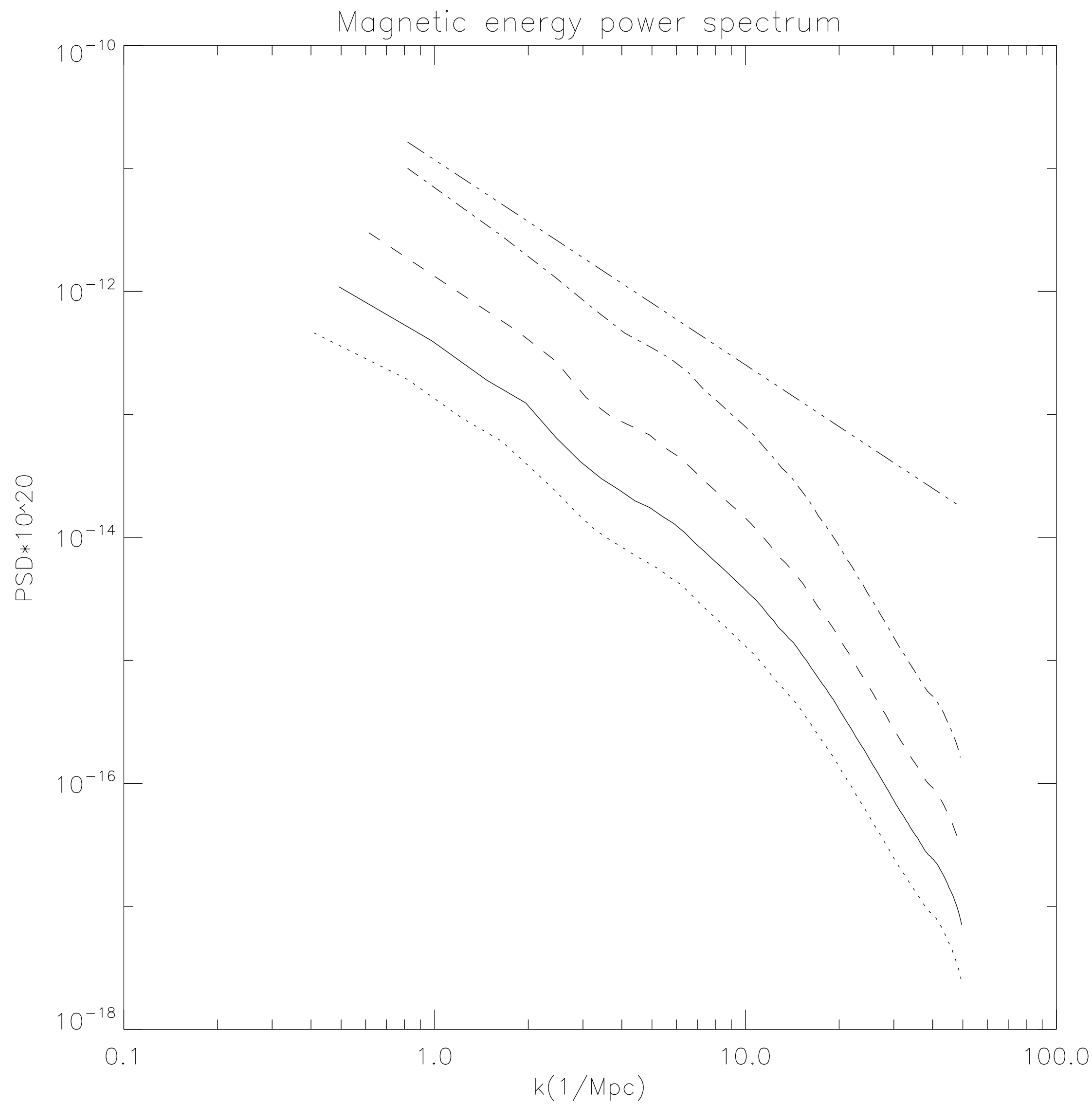

Fig. 3.— Three-dimensional power spectrum of the magnetic field energy in the galaxy cluster that forms at the center of the cluster. The dashed line represents a power law of index -5/3 for comparison. The lines correspond to different box sizes for which the power spectrum was calculated (dotted line: 15.36 Mpc, solid line: 12.80 Mpc, dashed line: 10.24 Mpc, dot-dashed line: 7.68 Mpc).

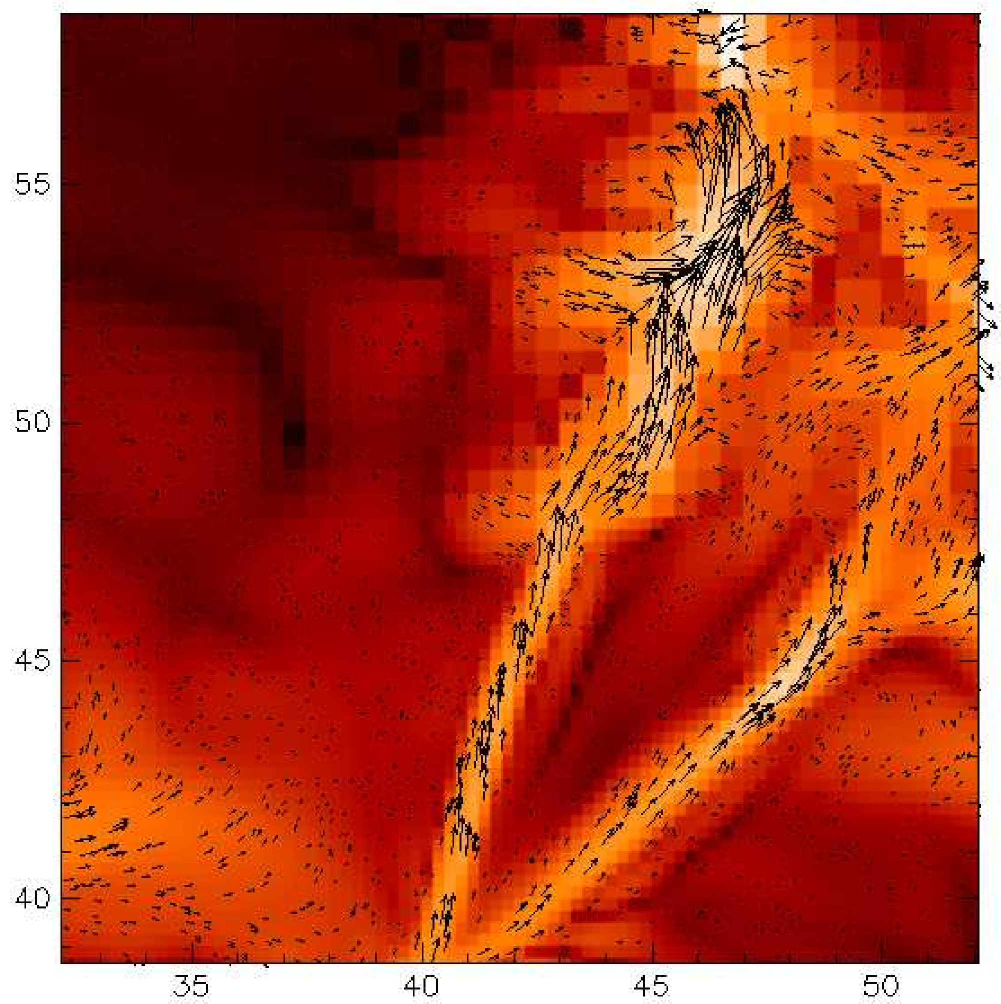

Fig. 4.— Magnetic field in a slice through two filaments in our computational box. The colors represent the logarithm of the magnitude of the magnetic field and the tickmarks denote Mpc. The lines show the orientation of the magnetic field in the plane of the plot.

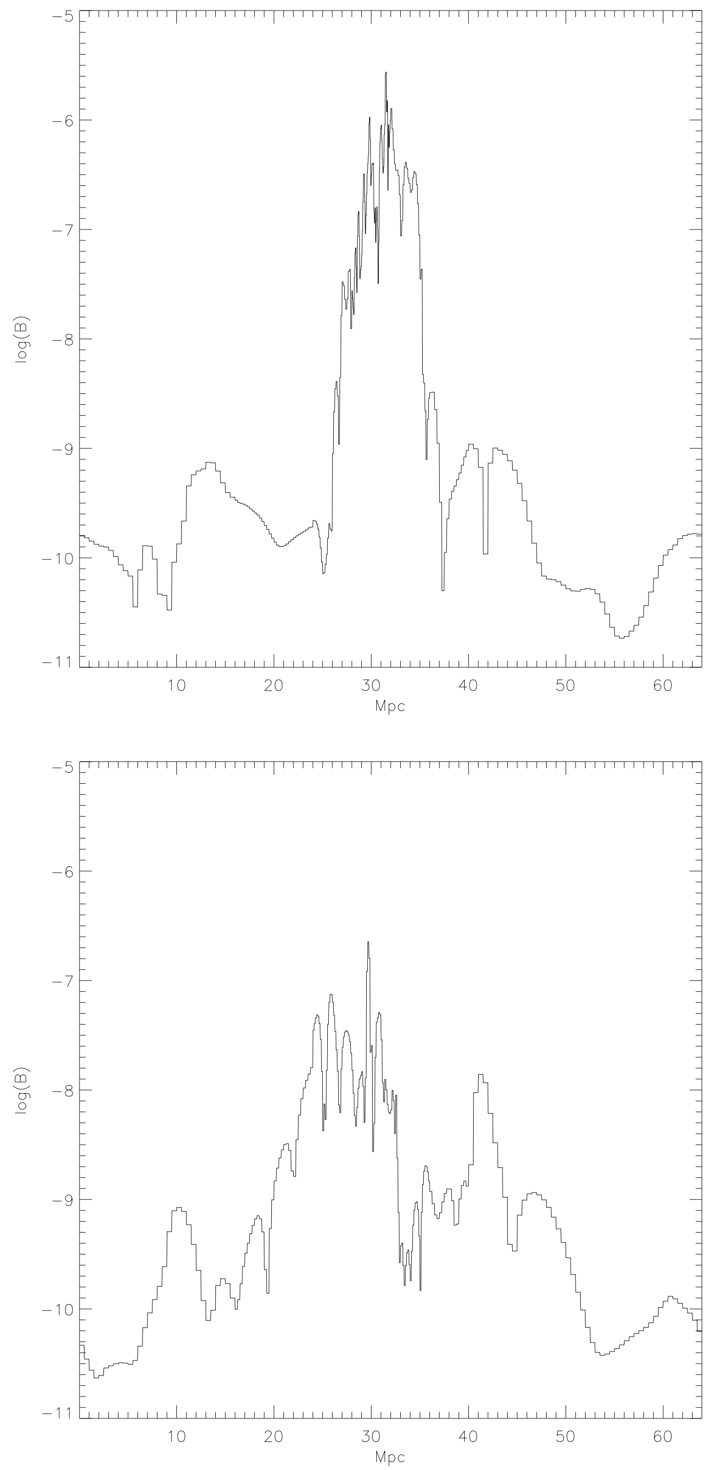

Fig. 5.— Profile of the magnetic field along a line that goes through the center of the cluster (top) and along a line that cuts through a filament (bottom).

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